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Influence of healing techniques on deformation of asphalt concrete

Saad Issa Sarsam[1]✉, **Husham Mohammed Al Tuwayyij**[2]

[1]Professor, Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
[2]MSc. Student, Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq

✉**Corresponding author:**
Email: saadisasarsam@coeng.uobaghdad.edu.iq

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ABSTRACT

Repeated and concentrated loading and environmental impactsare considered as a major challenge facing the serviciability of flexible pavement. Efforts on thedevelopment of innovative materials and techniquesfor asphalt pavement quality reservation and repair are going on, many of them related tocrack healing. Flexible pavement usually suffers distresses throughout its service life. Microcracks initiates and can heal itself under controlled conditions. In this investigation, iron filling was implemented as partical replacement of fine aggregates to support the healing process while both microwave induction heating andoven external heating techniques were adopted to control the healing process. Asphalt concrete specimens have been prepared with different percentages of iron filling and corresponding required asphalt content. Specimens were subjected to repeated indirect tensile stresses for 1200 repetitions in the pnumatic repeated load system PRLS. Specimens were allowed to heal after termination of the test using microwave and oven heating techniques. Specimens were returned to the PRLS and subjected to another cycle of stress repetition while the permanent deformation was monitored before and after healing. The healing performance of asphalt concrete was

investigated by observing the recovery of permanent deformation after healing. It was concluded that implementation of iron filling and induction heating exhibits a great impact on controling the deformation of asphalt concrete as compared with external heating technique.

Keywords: Crack Healing; Asphalt Concrete; Permanent Deformation; Induction Heating; Iron Filling

1. INTRODUCTION

Asphalt is a viscoelastic material where two phases can be considered: liquid phase (volatile) formed by maltenes and a solid phase formed by (asphaltenes). Therefore, theoretically, when a crack appears is closed byitself, but it would do it faster if the liquid part of bitumen increases. That can be done by mixing with less denseoil, known as rejuvenator as stated by Garcia et al., (2010). Self healing of asphalt concrete has some limitations; it is a slow process at ambient temperature and non-effective if the cracks are significant as reported by (Garcia, 2012). Hechuan et al, studied the effect of induction heating on asphalt binder aging in steel fibers modified asphalt concrete. The investigation showed that the asphalt binder inside asphalt concrete starts aging during induction heating process. This could be attributed to thermal oxygen reaction, and volatilization of the light components. Studies by (Sangadji & Schlangen, 2013) have demonstrated that microwave radiation maybe applied for crack healing purposes as well as onthe production and recycling of asphaltic pavements. Microwave industrial devices have already been designed especially for this application. Besides being effective onthe heating of asphalt mixtures, microwave heatingis less time consuming and considerabley reduces efforts required in terms of energy supply. Alakhrass (2018) studied the effect of adding iron powder on the property of the self-healing of the wearing layer in the asphalt mix. Samples were subjected to flexure stress by flexural fracture machine after being cooled to -20ºC, then samples were heated using induction heating device (Microwave) for fixed time interval to each sample, temperatures of samples were recorded, and again samples were fractured after cooled, flexural forces were recorded. Sun et al., (2014) applied microwave heating on steel slag asphalt mixtures. It was concluded that microwave heating could be implemented to promote the self-healing of steel slag asphalt mixture. Contreras and Garcia, (2016) believed that the microwave technology is more effective than induction heating to heal cracks in asphalt roads. Phan et al., (2018) analyzed the applicability of steel slag in the asphalt mixtures for the self-healing purpose using microwave heating technique. Test results suggested that adding two percent of steel wool fibers by weight of asphalt mixture provides the best healing level for both types of aggregate mixtures. The substitution of 30% normal coarse aggregate by the steel slag was promising due to its presence not only provides better healing results but also helps the whole mixture improve the load-displacement relationship with higher ductile behavior. Liu et al., (2018) stated that Induction heating is a valuable technology to repair asphalt concrete damage inside. However, through the induction heating process, the induced particles will release a large amount of heat which act on asphalt binder in a short time. It has been widely proven that asphalt concrete is a self-healing material and induction heating can magnify the healing ability to extend the pavement service life. Induction heating of asphalt concrete is a technique to increase the self-healing rate of the asphalt concrete material. It basically consists in adding electrically conductive fibers to the asphalt mixture. Then, with the help of an induction heating source, it is possible to heat the fibers locally and as a result, to heat the asphalt pavement and to heal the cracks as reported by Jendia et al. Al-Ohaly et al., (1988) studied the effect of microwave heating onadhesion and moisture damage of asphalt mixtures. Microwave treatment of asphalt mixtures is believed to have the potential to improve the adhesion between asphalt and aggregate. Magnetic induction heating and microwave heating technology could heat bituminous materials and heal cracks as reported by (Karimi et al., 2018). Microwave heating of asphalt binder may reduce potential risks which are related to human health during its production cycle. However, electrical and thermal conductivities of asphalt need to be modified to allow microwave heating, which can be achieved, for instance with the addition of a metallic material as reported by (Contreras et al., 2016). A Previous study by (Yang et al., 2016) had reported that self-healing in bituminous mixtures is possible if the temperature is raised high enough which can reduce the binder viscosity and allow the fusion of the cracks. Electromagnetic induction heating of mixtures with additives that raise electric conductivity is considered as the most frequently used technique. The study use inductive particles such as steel wool and graphite. The aim of this investigation is to assess the impact of iron filling and induction and external heating techniques on microcrack healing and permanent deformation of asphalt concrete.

2. MATERIALS AND METHODS

Asphalt Cement

Asphalt cement of penetration grade (40-50) produced from Al-Nasiriyah Refinery was implemented, the physical properties of asphalt binder are listed in Table 1.

Table 1 The Physical properties of asphalt cement

Property of Asphalt Cement	Test Conditions	ASTM, 2013 Designation No.	Test results	SCRB, 2003 Specification
Penetration	25°c, 100gm, 5sec	D5-06	44	40-50
Softening Point	-	D36-95	49	-
Ductility	25°c, 5cm/min	D113-99	140	>100
Specific Gravity	25˚c	D70	1.03	
Flash Point	Cleave land open cup	D92-05	302	>232
After thin film oven test D1754-97				
Retained Penetration of Residue (%)	25°c, 100gm, 5sec	D5-06	81	>55
Ductility of Residue	25°c, 5cm/min	D113-99	95	>25

Coarse and Fine Aggregates

The Aggregates used in this investigation are locally available in the quarries of Badra city in Wasit province and these quarries are usually used frequently in paving work by government companies in the southern provinces. Table 2 demonstrates the physical properties of coarse aggregates while Table 3 shows the properties of fine aggregates.

Table 2 Properties of Coarse Aggregates

Property	ASTM, 2013 Designation No.	Test results	SCRB, 2003 Specification
Bulk Specific Gravity of Coarse Aggregate	C127-88	2.618	-
Apparent Specific Gravity of Coarse Aggregate	C127-88	2.688	-
Absorption in percent of Coarse Aggregate	C127-88	1 %	-
Percentage of Fractured Particles in Coarse Aggregate	D5821-13	92%	Min: 90%
Resistance to Abrasion (Los Angeles)	C131/C131M-13	23%	Max: 30%

Table 3 Properties of Fine Aggregates

Property	ASTM, 2013 Designation No.	Test results
Bulk Specific Gravity G_B of Fine Aggregate	ASTM-C128-01	2.622
Apparent Specific Gravity G_A of Fine Aggregate	ASTM-C128-01	2.693
Absorption in percent of Fine Aggregate	ASTM-C128-01	1.1%

Mineral Filler (Limestone dust)

Limestone dust was used as a filler, it was obtained from asphalt plant of the Ministry of Housing and Construction. The physical properties of the filling material are listed in Table 4.

Table 4. Properties of Mineral Filler

Property	Test results
Percent passing sieve No. 200	95
Specific gravity	2.850
Specific surface area (m^2/Kg)	355

Additive (Iron Filling)

The iron filing used in this work was brought locally from the blacksmith's factories scattered in Samawah province. One size of iron filling was implemented, it was sieved to pass through Sieve No. 8 (2.36 mm) and retained on Sieve No. 50 (0.300 mm). Thespecific weight of iron filings was 7.14gm/cm^3. Figure 1 shows the iron filling implemented in this work.

Figure 1 Iron Filling

Selection of Combined Gradation

Asphalt concrete was prepared for wearing course type 111-B according to the gradation limitations of SCRB, 2003demonstrated in Figure 2.

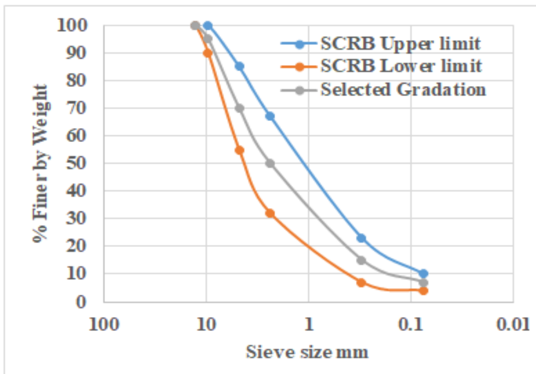

Figure 2 SCRB, 2003 Limitations of Aggregate Gradation

Preparation of Asphalt Concrete Specimens

The aggregates were dried in an oven to a constant weight at 110ºC, then sieved to different sizes, and stored separately. Coarse and fine aggregates were combined with mineral filler to meet the specified gradations of asphalt concrete layer as per (SCRB, 2003) specifications. The combined aggregates mixture was heated to 150ºC before it was mixed with asphalt cement. The iron filling was added as partial replacement of fine aggregate in percentages of (0, 2, 4, 6, 8)%. The asphalt cement was heated to 150ºC, then it was added to the heated aggregates to achieve the desired amount and mixed thoroughly with the aid of mechanical mixer for 2 minutes until all of the aggregate particles were coated with thin film of asphalt binder. Marshall specimens were prepared in accordance with (ASTM D1559, 2013) using 75 blows of Marshall hammer on each face of the specimen. Specimens with combination of iron filling and asphalt cement were prepared and the optimum asphalt content for each combination was evaluated. Table 6 exhibit the optimum asphalt requirements for each percentage of iron filling. Table 7 demonstrates the Marshall and volumetric properties of the design mixture.Specimens were tested in triplicate, while the average value was considered for further analysis. Figure 3 shows part of the prepared specimens. Deatails of determination of optimum asphalt and iron filling were reported by (Al Tuwayyij, 2020).

Table 6 Optimum Asphalt Content for Iron Filling Percentages

Percent Iron Filling %	Optimum Asphalt Content %
0	5.2
2	5.1
4	5
6	4.9
8	4.8

Table 7 Marshall and Volumetric Properties of the Design Mixture

Property	Value	SCRB, 2003 Specifications
Iron Filling %	5	---
Optimum asphalt content %	4.9	4-6
Air voids %	4.1	3-5
Unit Weight	2.410	---
Marshall stability (kN)	11.4	8 (kN) minimum
Marshall Flow (mm)	2.8	2-4 (mm)
VMA(%)	15.6	14(%) Minimum
Voids Filled With Asphalt %	76	-----

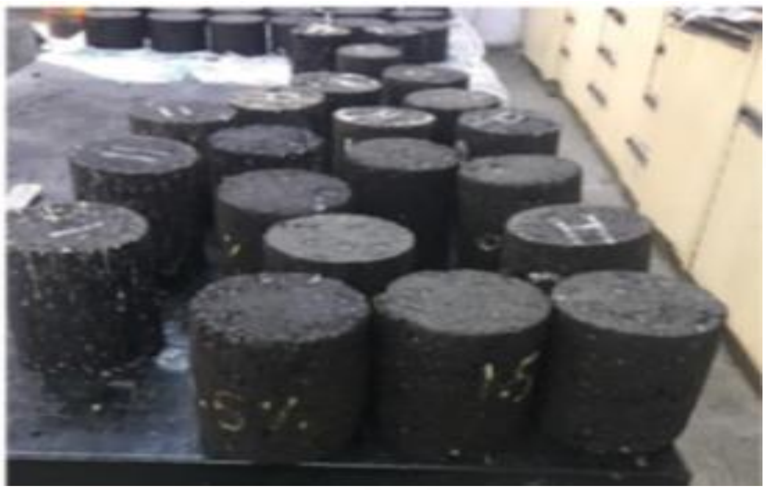

Figure 3. Part of the Prepared Specimens

Repeated Indirect Tensile Stresses Test

The repeated indirect tension stress test as specified by (ASTM, 2013) was conducted using the pneumatic repeated load system (PRLS). The test was performed on Marshall specimens, 102 mm in diameter and 63.5 mm in height. Repetitive indirect tensile loading was applied to the diametral specimen and the vertical strain is monitored under the load repetitions. Diametral loading is applied with a constant loading frequency of 60 cycles per minute, and the loading sequence for each cycle is 0.1 seconds for load duration and 0.9 seconds for rest period. Load repetitions was applied under constant stress level of 0.138 MPa, while the testing temperatures of (25) °C was implemented in the test. Figure 4 exhibit the repeated load sequance implemented while figure 5 exhibit the repeated tensile stress test setup and the PRLS. Specimens were subjected to the application of repeated indirect tensile stresses of 600 and 1200 load repetitions.

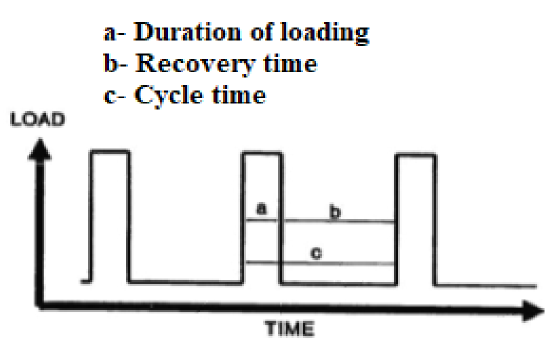

Figure 4 Repeated tensile stress loading sequance implemented

Figure 5 PRLS and Repeated Indirect Tensile Stress Test Setup

Microcrack Healing Process

Two techniques for microcrack Healing have been adopted in this work, the first techniqu was healing with the aid of the external heating. The second technique was the induction heating with the aid of microwave oven. The healing procedure for both techniques can be summerized as follow:

External Heating

After applying 600 or 1200 load repetitions to allow for the initiation of micro cracks, the test was terminated. Specimens were withdrawn from the PRLS testing chamber and stored in an oven for 120 minutes at 60°C to allow for microcrack healing as recommended by (Qiu et al, 2013); (Sarsam, 2015); and (Sarsam, 2016). Healing occurred in the asphalt concrete mixture specimens due to the reduction in the viscosity of asphalt cement by external heating. The specimens were cooled at room temperature for 24 hours, then transferred to the PRLS chamber. Specimens were conditioned by placing in the PRLS chamber at temperature (25ºC) for 120 minutes. Specimens were subjected to another cycle of 600 or 1200 load repetitions. After first and second cycles of load repetitions in PRLS device, and before and after healing process, the specimens were subjected to indirect tensile strength determination.

Figure 6 Heating techniques adopted

Induction Heating

After applying 600 or 1200 load repetitions to allow for the initiation of micro cracks, the test was terminated. Specimens were withdrawn from the PRLS testing chamber and stored in the microwave oven of (900 Watt) for 150 second then the cooling process

was carried out by placing the specimens at room temperature of 25ºC for 120 minutes. The temperature of the specimens were recorded after the heating process and referred as (healing temperature). Figure 6 demonstrates the heating techniques adopted. Table 8 illustrates theinfluence of Iron Filling and Induction Heating on healing temperature of asphalt concrete specimens.

Table 8 Influence of Iron Filling and Induction Heating on Healing Temperature

Percent Iron Filling	Temperature Before Induction Heating °C	Temperature After Induction Heating °C	Percent Increase inHealing Temperature
0	20	65	225
3	20	72	260
5	20	83	310
7	20	92	365

3. RESULTS AND DISCUSSION

Table 9 exhibit the permanent deformation of asphalt concrete specimens (before and after) microcracks healing due to practicing 600 indirect tensile stress load reprtitions at 20°C. It can be noted that the permanent deformation decreases after healing regardless of the heating technique implemented. The maximum reduction in permanent deformation was (39.3 and 32) % for induction and external heating techniques respectively. The healing ratio increases after implementation of iron fillings up to 5% of iron filling content, then the rate of increase decreases. The maximum healing ratio was 2.45 and 2.22 for induction and external heating techniques respectively. It can be observed that implementation of microwave induction heating exhibit more reduction in permanent deformation as compared to the oven external heating technique. The higher healing temperature in the case of induction heating as illustrated in Table 8 may be attributed to the fact that the induction heating increases the temperature inside the mixture, while the iron filling absorbs such high temperature which support melting of asphalt binder and healing the microcracks. The heating speed at asphalt mixture with microwave inductionheating was much higher than that with external heatingof 60°C while the temperature distribution within the asphaltmixture under induction heating was quite uniform. The effective heating depth of microwave induction heating is used to bemuch higher than thatof external heating. Similar behavior was reported by (Hechuan Li et al., 2019); and (García et al. 2013). Asphalt concrete can be healed quickly, because asphalt binder behaves as a near-Newtonian fluid when its temperature is above the softening point of the binder. As the provided healing temperature increases, a quick crack closer could be achieved. Similar finding was reported by Tang et al, (2016).

Table 10 illustrates the permanent deformation of asphalt concrete specimens (before and after) microcracks healing due to practicing 1200 indirect tensile stress load reprtitions at 20°C. Similar behavior of reduction in permanent deformation after healing could be detected. It can be noted that the permanent deformation decreases after healing regardless of the heating technique implemented. The maximum reduction in permanent deformation was (26.3 and 18.7) % for induction and external heating techniques respectively.

Table 9 Permanent Deformation of Specimens after 600 Load Cycles

% of Iron Filings in specimen	Permanent Deformation (εp)							
	Microwave				Oven			
	Before Healing	After Healing	Rate of Decrease	Healing Ratio	Before Healing	After Healing	Rate of Increase	Healing Ratio
Control	15500	13000	16%	1	18000	15400	14.4%	1
3%	13000	10700	17.7%	1.1	17300	14700	15.4%	1.07
5%	14000	8500	39.3%	2.45	16700	11300	32%	2.22
7%	16500	13600	17.5%	1.09	21300	17700	16.9%	1.17

The healing ratio increases after implementation of iron fillings up to 5% of iron filling content, then the rate of increase decreases. The maximum healing ratio was 1.46 and 1.41 for induction and external heating techniques respectively.It can be observed that the healing ratio for the specimens after practicing 1200 load repetitions is lower than that of specimens practiced 600 load repetitions by a range of (36-40)% for 5% of iron filling.

Figure 7 exhibit the influence of iron filling and heating techniques on microcrack healing of asphalt concrete specimens subjected to both load repetitions of 600 and 1200. It shows higher reduction in permanent deformation after induction heating as

compared to the case of external heating.In fact, at 1200 load repetitions, the damage of the specimen start to change from microcrack to macrocrack as stated by (Sarsam and Hamdan, 2019).

Table 10 Permanent Deformation of specimens in 1200th Cycle

% of Iron Filings in specimen	Permanent Deformation (εp)							
	Microwave				Oven			
	Before Healing	After Healing	Rate of Decrease	Healing Ratio	Before Healing	After Healing	Rate of Increase	Healing Ratio
Control	25000	19500	22%	1	25000	21700	13.2%	1
3%	18500	14100	23.7%	1.07	23300	20000	14.3%	1.08
5%	19000	14000	26.3%	1.46	23000	18700	18.7%	1.41
7%	17000	15500	8.8%	0.48	27700	25300	8.4%	0.63

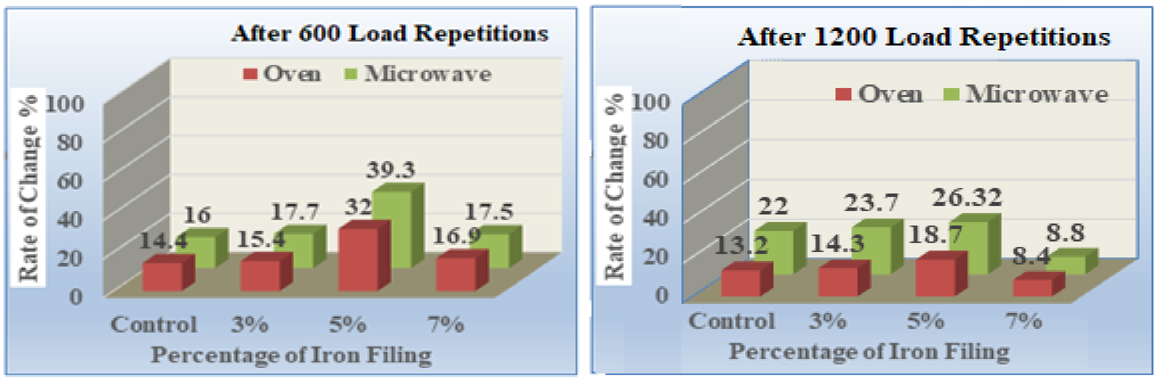

Figure 7 Permanent deformation after 600 and 1200 Load Repetitions

The damage in the form of microcrack occurred at such high loading sequence and the healing by both heating techniques can hardly maintain original state of control specimens. On the other hand, implementation of iron filling exhibit improvement in controlling the deformation under both heating techniques. Specimens with 5% iron filling shows superior control of deformation as compared to othe iron filling content or control mixture.

Figure 8 demonstrate the influence of iron filling content and microwave induction heating on deformation parameters (intercept and slope). The intercept represents the permanent microstrain at N=1 (N is the number of load cycles).Asthe value of the intercept gets higher; it indicates a larger strain and potential of permanent deformation. On the other hand, the slope refers to the rate of change in the permanent microstrain. It is referred as a function of the change in loading repetitions in the log-log scale.High slope of the mixture indicates an increase in the material deformation rate, hence, less resistance against rutting.A mixture with low slope is preferable as it prevents the occurrence of rutting, (Sarsam, 2015).

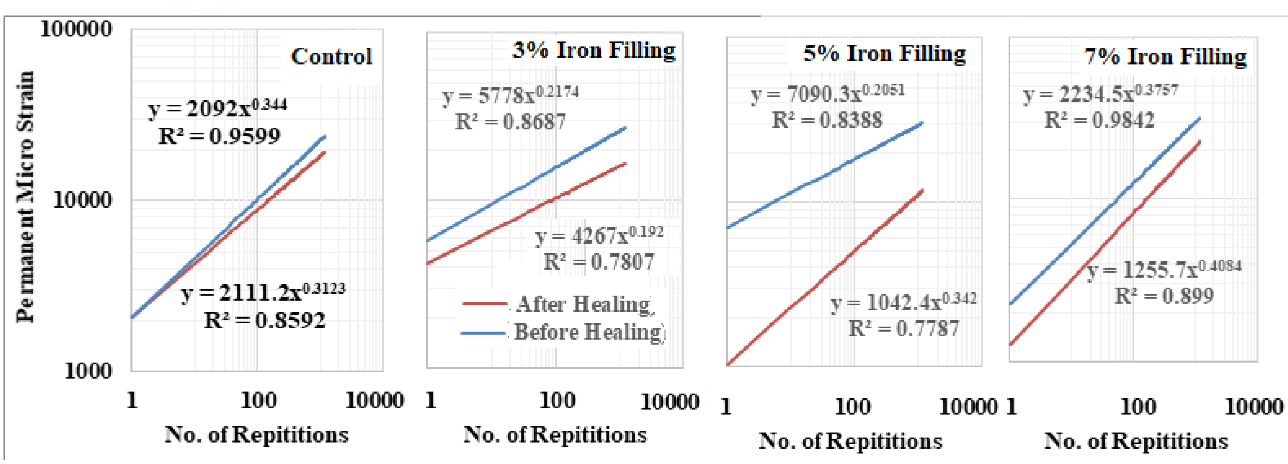

Figure 8 Influence of Iron Filling and Microwave Induction Heating on Permanent Deformation

Sharp slope could be detected for control mixture before and after healing as compared to other specimens with iron filling. When 3% of iron filling was implemented, the slope gets lower and gentler, but the intercept increases for specimens before and after healing. When (5 and 7)% of iron filling was added which is supposed to be the optimum additive content, the intercept after healing decreases indicating stiffer mixture condition. It can be noted that microwave induction heating has significant influence on permanent deformation, and it increases as the iron filling content increase.

As demonstrated in Figure 9, the variation in the slope was not significant among control and iron filling specimens when external heating by oven was implemented before and after healing. On the other hand, the intercept decreases when iron filling was introduced regardless of the healing condition of the specimens. It can be observed that implementation of 5% of iron filling and external heating can significantly increase the resistance to permanent deformation of asphalt concrete.

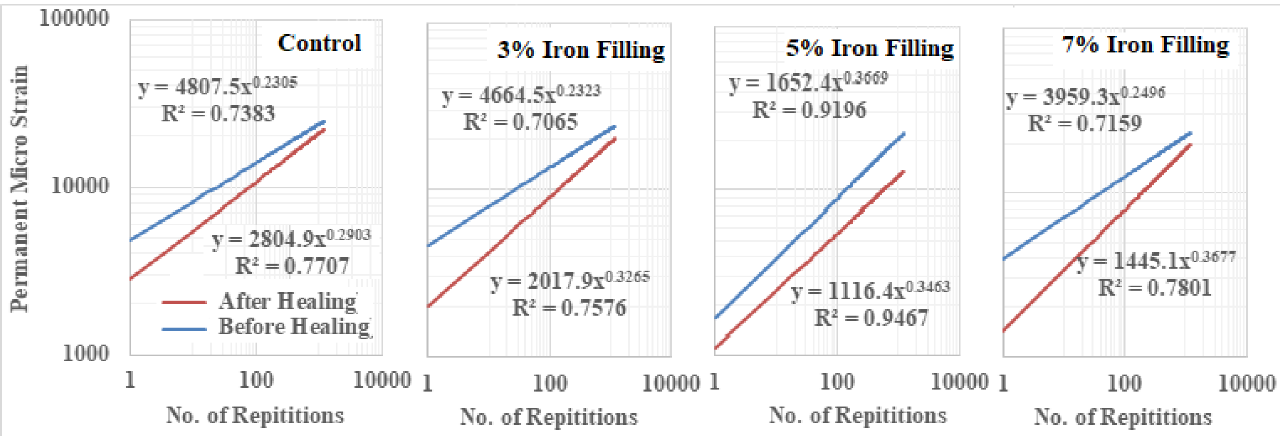

Figure 9 Influence of Iron Filling and Oven External Heating on Permanent Deformation

Table 11 exhibit the details of permanent deformation parameters for both heating techniques. Negative influence of iron filling could be detected on intercept for specimens before microwave heating. When induction heating was introduced, the intercept which represent the permanent strain decreases by (26, 85, and 43) % for (3, 5, and 7) % of iron filling respectively. On the other hand, when external heating was introduced, the permanent strain decreases by (57, 32, and 63) %for (3, 5, and 7) % of iron filling respectively.

Table 11 Permanent Deformation Parameters

% of Iron Filings in specimen	Repeated ITS Load after 1200 loading cycles							
	Microwave				Oven			
	Intercept		Slope		Intercept		Slope	
	Before Healing	After Healing	Before Healing	After Healing	Before Healing	After Healing	Before Healing	After Healing
Control	2092	2111	0.344	0.8592	4807	2804	0.2305	0.2903
3%	5778	4267	0.2174	0.192	4664	2017	0.2323	0.3265
5%	7090	1042	0.2051	0.342	1652	1116	0.3669	0.3463
7%	2234	1255	0.3758	0.4084	3959	1445	0.2496	0.3677

4. CONCLUSION

Based on the testing program conducted, the following conclusions may be drawn.

1- The maximum reduction in permanent deformation was (39.3 and 32) % for induction and external heating techniques respectively after 600 load repetitions.

2- The healing ratio increases after implementation of iron fillings up to 5% of iron filling content, then the rate of increase decreases. The maximum healing ratio was 2.45 and 2.22 for induction and external heating techniques respectively after 600 load repetitions.

3- The maximum reduction in permanent deformation was (26.3 and 18.7) % for induction and external heating techniques respectively after 1200 load repetitions.

4- The maximum healing ratio was 1.46 and 1.41 for induction and external heating techniques respectively after 1200 load repetitions.
5- When induction heating was introduced, the permanent strain (intercept) decreases by (26, 85, and 43) % for (3, 5, and 7) % of iron filling respectively.
6- When external heating was introduced, the permanent strain (intercept) decreases by (57, 32, and 63) % for (3, 5, and 7) % of iron filling respectively.

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Conflicts of Interest: The authors declare no conflict of interest.

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